LBL-28755
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Submitted to Physics Letters B

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March 1990

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Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

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LBL-28755

Parton shadowing effect on the J/ψ production *

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March 16, 1990

Abstract

A model is presented that explains the observed J/ψ suppression in hadron - nucleus and nucleus - nucleus collisions as due to parton shadowing. Two extreme regimes are found for which the J/ψ production cross section have a different behaviour with the nuclear mass numbers. The regime for low values of A is responsible for the deviations from linearity observed in hA collisions while large AB regime explains the big suppression observed in nucleus - nucleus high E_T events.

*This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U. S. Department of Energy under Contract No. DE-AC03-76SF00098 and by the Spanish Ministry of Education and Sciences/Fulbright program

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Since NA38 collaboration first reported that a significant decrease of the ratio $R = \sigma^{AB\to\psi}/\sigma^{AB\to(\mu^+\mu^-)_{DY}}$ has been observed in high energy nucleus - nucleus collisions, when required transverse energy E_T of the final state was incremented [1] , there has been much excitement about the possibility of having found a signal of Quark - Gluon Plasma formation. The suppression of J/ψ particles production in the QGP had been predicted as a consequence of colour screening [2]. It is not common that a theoretical prediction is so closely followed by its experimental corroboration. Nonetheless, to conclude that such a relative suppression is caused by colour screening in QGP a careful examination of all other possible sources of this effect on the ground of non - QGP physics is imperative.

Several works have been published with this propose. In ref. [3] we tried to explain the behaviour of R as a consequence of the absorption of the J/ψ particle by the nucleons via J/ψ - nucleon inelastic collisions. We extract de J/ψ - N absorptive cross section ($\sigma_{abs}^{\psi N}$) so as to obtain the A^α behaviour of pA J/ψ production cross section given in ref. [4]. But we could not get the right suppression of R for the different E_T bins, and we pointed out that contribution from another component of the suppression, that would behave as $A^{0.7}$ as suggested in ref. [4], has to contribute as much as the 50% to obtain the right suppression. On the other hand, it is difficult to justify such a large value of $\sigma_{abs}^{\psi N}$ especially when the momentum fraction of the J/ψ is closed to 1 [5].

Other works tried to explain the effect as due to the absorption of the J/ψ by the secondary particles [6,7]. In this case similar problems are present when the values of the corresponding absorption cross section and particle densities have to be justified.

Here I present an explanation of the J/ψ suppression as a consequence of parton shadowing. The structure of the letter is as follows. First I analyse how shadowing appears in hard scattering processes. Next, I discuss the behaviour of J/ψ production cross sections as a function of nuclear size. This is used to understand the mentioned J/ψ suppression and the origin of the $A^{0.7}$ component of ref. [4].

Shadowing is a common phenomenon that can eventually appear in any collision experiment in which the density of targets is large enough to prevent a linear behaviour of the scattering particles rate with the number of targets, and it was extensively studied in the case of high energy nucleus - nucleus collisions. In this context shadowing appears because at such high energy no effect from nuclear structure are expected to be important and the overall interaction is a consequence of multiple nucleon - nucleon collisions. One can be tempted to think that the cross section should grow linearly with A in the case of pA collisions, and with AB in AB collisions. However, nuclear thickness are high enough compared with $1/\sigma_{NN}$ (σ_{NN} being the nucleon - nucleon inelastic cross section) to prevent such a linear relation. The optical approximation to

the Glauber - Gribov model gives a full description of these kind of scattering processes [8]. The nucleus - nucleus inelastic cross section is given by:

$$\sigma_{AB} = \int d^2\vec{b}[1-(1-\sigma_{NN}T_{AB}(\vec{b}))^{AB}] \quad . \tag{1}$$

The profile function is defined as

$$T_{AB}(\vec{b}) = \int d^2\vec{s}\,T_A(\vec{s})T_B(\vec{b}-\vec{s}) \quad . \tag{2}$$

$$T_A(\vec{b}) = \int dz\,\rho_A(\vec{b},z) \quad . \tag{3}$$

Where ρ_A is the nucleon probability density inside the nucleus. The corresponding expression for pA collisions is obtained substituting $T_{AB}(\vec{b})$ by $T_A(\vec{b})$ in equation (1), and AB of the exponent by A.

It is clear from equation (1) that linearity is only attained if $\sigma_{NN}T_{AB}(\vec{b})AB \ll 1$, having a behaviour of the cross section of the type $(AB)^{\frac{2}{3}}$ ($A^{\frac{2}{3}}$ in pA), for the case $(1-\sigma_{NN}T_{AB}(\vec{b}))^{AB} \ll 1$ corresponding to a surface term. This last condition is obtained due either to a large value of $\sigma_{NN}T_{AB}(\vec{b})$ or to a large value of AB.

This model can be applied to the study of cross sections of a particular kind of events characterized by the fact that at least one nucleon - nucleon collision is of this sort. The expression for the cross section of this events are obtained from (1) substituting σ_{NN} by the associated nucleon - nucleon cross section σ_C .

Production of J/ψ in hadronic collisions is originated in a hard parton - parton scattering of the kind $q\bar{q} \rightarrow c\bar{c}$ or $gg \rightarrow c\bar{c}$. Taking into account typical values of these parton - parton cross sections and the typical time scales of these processes we can assume that they take place in a small region when compared with the hadronic dimensions. In a similar way as in the nucleus - nucleus case discussed in the previous paragraph, we can neglect hadrons structure effects and assume that hard hadronic interactions are the consequence of an independent superposition of parton - parton interaction. This is very different from what one would expect in a soft hadronic collision, in which case, due to small Q^2 of the reaction, the interaction region is of the order of the hadron size and factorization of the process cannot be applied (see fig. 1). Proper treatment of this problem has to incorporate unitarity, which forbids linear growth of the cross section with the target size as can be seen from the following argument. As the transverse area would increase with the target size as a surface term, $A^{\frac{2}{3}}$, a linear increase of the cross section would mean an effective increment of the interaction probability per unit area that would go as $A^{\frac{1}{3}}$ and can eventually reach values greater than 1. I am going to apply the Glauber Gribov model at the

parton level to see if it can help to understand the J/ψ production since it incorporates unitarity in a natural way.

Let us think of a hadron in hadron-hadron collision (a-b collision), as composed of n_q quarks, $n_{\bar{q}} = n_q - 3B$ (B being the baryon number) antiquarks and n_g gluons. If we neglect fluctuations of parton-parton $\rightarrow J/\psi$ cross sections ($\sigma_{q\bar{q}}$ and σ_{gg}) due to the structure function and take them as effective values we can write the following expression for the $ab \rightarrow J/\psi$ cross section:

$$\sigma^{ab\rightarrow J/\psi} = \sum_{n_q^a}\sum_{n_q^b}\sum_{n_g^a}\sum_{n_g^b} P(n_q^a, n_g^a) P(n_q^b, n_g^b) \sigma_{ab}^{n_q^a, n_g^a, n_q^b, n_g^b} \quad . \tag{4}$$

Where $P(n_q, n_g)$ is the probability of having those values for the parton composition of the hadron, and $\sigma_{ab}^{n_q^a, n_g^a, n_q^b, n_g^b}$ is given by:

$$\begin{aligned} \sigma_{ab}^{n_q^a, n_g^a, n_q^b, n_g^b} &= \int d^2\vec{b}[1-(1-\sigma_{q\bar{q}} t_{ab}^{(q)}(\vec{b}))^{n_q^a n_{\bar{q}}^b}] + \int d^2\vec{b}[1-(1-\sigma_{q\bar{q}} t_{ab}^{(q)}(\vec{b}))^{n_{\bar{q}}^a n_q^b}] + \\ &+ \int d^2\vec{b}[1-(1-\sigma_{gg} t_{ab}^{(g)}(\vec{b}))^{n_g^a n_g^b}] \quad . \end{aligned} \tag{5}$$

Here $t_{ab}^{(q)}(\vec{b})$ ($t_{ab}^{(g)}(\vec{b})$) is defined as $T_{AB}(\vec{b})$ of equation (1), using now the quark (gluon) probability density inside the hadron, in this respect I have neglected differences between valence quarks, sea quarks and sea antiquarks. These parton profile function has to incorporate some of the kinematical constraints of the system which are expected to be important due to the large J/ψ mass, so they have to be interpreted as the convolution of the probability densities on the impact parameter plane of finding a parton (quark, antiquark or gluon), and have to be normalized to the probability of having a pair of partons from each hadron with the energy required to produce the desired final state.

If $\sigma_{q\bar{q}} t_{ab}^{(q)}(\vec{b}) \ll 1$ and $\sigma_{gg} t_{ab}^{(g)}(\vec{b}) \ll 1$ we can neglect higher order terms when expanding $\sigma^{ab\rightarrow J/\psi}$ in powers of these two quantities:

$$\begin{aligned} \sigma^{ab\rightarrow J/\psi} &\simeq \sigma_{q\bar{q}} < n_q^a n_{\bar{q}}^b + n_{\bar{q}}^a n_q^b > -\frac{1}{2}\tau_{q\bar{q}}^2 \sigma_{q\bar{q}}^2 < n_q^a n_{\bar{q}}^b (n_q^a n_{\bar{q}}^b - 1) + n_{\bar{q}}^a n_q^b (n_{\bar{q}}^a n_q^b - 1) > + \\ &+ \sigma_{gg} < n_g^a n_g^b > -\frac{1}{2}\tau_{gg}^2 \sigma_{gg}^2 < n_g^a n_g^b (n_g^a n_g^b - 1) > \quad . \end{aligned} \tag{6}$$

Where $< ... >$ means average over all parton configurations and

$$\tau_{q\bar{q}}^2 = \int d^2\vec{b}\,[t_{ab}^{(q)}(\vec{b})]^2 \quad , \quad \tau_{gg}^2 = \int d^2\vec{b}[t_{ab}^{(g)}(\vec{b})]^2 \quad . \tag{7}$$

These quantities have dimensions of $(area)^{-1}$, it is obvious from (6) that its inverse has to be the characteristic overlapping area between two hadrons weighted with the probability of finding a pair of partons with energy enough to produce a J/ψ (s_{ov}), when at least one such a particle is produced. This s_{ov} can be related to the single and double J/ψ production (σ_ψ, $\sigma_{\psi\psi}$) to the lowest order in these two quantities in a simple manner:

$$\frac{s_{ov}}{s_h} \simeq \sqrt{\frac{\sigma_{\psi\psi}}{< n_q^a n_{\bar{q}}^b + n_{\bar{q}}^a n_q^b + n_g^a n_g^b - 1 > \sigma_\psi}} \quad , \tag{8}$$

where s_h is the transverse hadrons size. All this suggest that the quadratic terms in eq. (6) have a clear interpretation as screening corrections of the type discussed in ref. [3].

While we move from hadron - hadron collisions to hadron - nucleus collisions we have to change two things. First of all, we have to replace $t_b(\vec{b})$ by $t_A(\vec{b})$ which will be the result of the convolution of the nuclear profile functions (eq. (3)) with $t_b(\vec{b})$. Second, the number of parton constituents will change linearly with A. As a consequence we get the next functional form for the cross section.

$$\sigma^{aA \to J/\psi} \simeq kA - k'A^2 \quad . \tag{9}$$

With k and k' positive constants, linear and quadratic with the parton - parton cross sections, respectively. Corrections to equation (9) would come both from higher order terms in (6) and non zero order terms in the expansion of the corresponding τ^2's as a function of A.

As far as $k'A/k$ is small, we are justified in using expression (9) to interpret the experimental data. In ref. [9] data on J/ψ production in $\pi^- A$ and $\bar{p}A$ at 125 GeV/c collisions were collected and a quadratic fit to the dependence of the $\pi^- A \to \psi$ cross section on A was done on purely empirical grounds. For $k = 63.17 \pm 2.0$ and $k' = 0.11 \pm 0.01$ (in nbarns) an impressively good fit to the 5 points available was obtained, as shown in fig. 2. In order to understand the meaning of these two values we have to have an estimate of the value of s_{ov}/s_h mentioned above. In [10] values of double J/ψ production cross section in proton - nucleus collisions at 400 GeV/c has been presented which allows us to estimate an order of magnitude for s_{ov}/s_h of $10^{-2}(< n_q^a n_{\bar{q}}^b + n_{\bar{q}}^a n_q^b + n_g^a n_g^b - 1 >)^{-2}$ which is compatible with the values of k and k' as can be easily seen. The small value of the ratio s_{ov}/s_h is a consequence of the kinematical constraints, and suggest a picture in which J/ψ particle produced in a peripheral hadronic collision meaning that s_{ov} is small enough to prevent multiple J/ψ production. This is unlikely to happen when the production of lighter particles is observed since energy constraints are expected to be less significant. Is worth noting that when J/ψ

production at large momentum fraction is studied, one should expect a decrease in the value of s_{ov} due to the reduction of the allowed phase space making the second term in (9) to be more important. This is what is experimentally observed [9].

Thanks to equation (9) we can also understand why a linear behaviour of $\sigma^{aA\to J/\psi}$ with A is observed when high p_T J/ψ particles are triggered, since $\sigma_{q\bar{q}}$ and σ_{gg} decrease with the transverse momentum exchanged (Q_T) as $1/Q_T^2$, making the second term in (9) negligible for large enough values of Q_T.

The generalization to nucleus - nucleus collisions is straight forward. The cross section is obtained from (4) multiplying the exponents by AB

$$\begin{aligned}\sigma^{AB\to J/\psi} &= \sum_{n_q^a}\sum_{n_q^b}\sum_{n_g^a}\sum_{n_g^b} P(n_q^a,n_g^a)P(n_q^b,n_g^b)\times \\ &\times\{\int d^2\vec{b}[1-(1-\sigma_{q\bar{q}}t_{AB}^{(q)}(\vec{b}))^{ABn_q^an_q^b}]+\int d^2\vec{b}[1-(1-\sigma_{q\bar{q}}t_{AB}^{(q)}(\vec{b}))^{ABn_q^an_q^b}]+ \\ &+\int d^2\vec{b}[1-(1-\sigma_{q\bar{q}}t_{AB}^{(g)}(\vec{b}))^{ABn_g^an_g^b}]\} \qquad , \end{aligned} \tag{10}$$

where $t_{AB}(\vec{b})$ are the generalized parton - nuclear profile functions. Again, in situations in which one can assume that $\sigma_{q\bar{q}}t_{ab}^{(q)}(\vec{b})$ and $\sigma_{gg}t_{ab}^{(g)}(\vec{b})$ are much smaller than 1, we should get a quadratic form for the cross section as a function of AB substituting A by AB in (9). However, when high E_T events are triggered, contributions from very central collisions are dominant and every thing approximately works as if we have a large effective value of nuclear mass numbers, $AB^{eff.}(E_T)$. In fact, if equation (9) is used to compute the total $S^{32}Pb^{207} \to J/\psi$ total cross section (with no E_T cut) assuming the same order of magnitude of k and k' we see that $(k'AB)/k \sim 10$ which makes the approximation unreasonable. Under these conditions, equation (10) measures the transverse interaction area which is a surface term, and the cross section will behave as $A^{\frac{2}{3}}$ in the sens of ref. [3,4] In this way, we can understand the large J/ψ suppression with increasing E_T since it contains the strongly absorbed component of ref. [3].

One still may wonder why Drell - Yan cross sections is linear with A. In principle it can be said that in the region of the J/ψ mass, parton - parton Drell - Yan cross sections are orders of magnitude smaller than the corresponding values for J/ψ production and the quadratic term in (9) can be dropped. But still, there is another reason. Drell - Yan $\mu^+\mu^-$ pair production is an electromagnetic process and its long range character prevent us from applying the same arguments that lead to the Glauber - Gribov model since clear statement about the interaction area cannot be used.

I have presented a model, based on parton - parton shadowing, that can help us to understand the strong suppression of the J/ψ in AB collisions with increasing E_T

trigger. It can explain the deviation from linearity of hadron-A J/ψ production cross section as a function of the nuclear mass number A, giving the right functional form. The two suppression components mentioned in ref. [3,4] can be extracted from this model as the behaviour of the cross section in two different regimes. I want to stress that the kind of shadowing discussed here shouldn't be confused with the one related to the modification of the parton structure functions due to nuclear effects mentioned in [9].

Acknowledgments

I have been benefited from discussions with Dr. M. Gyulassy, Dr. M. Grabiak and Dr. R. Vogt to whom I want to express my gratitude.

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Figure captions

- **Figure 1.** Pictorial representation of a hadron as seen under small Q^2 (a) and large Q^2 (b) processes.
- **Figure 2.** $\pi^- A \rightarrow J/\psi$ Cross section data compared with the quadratic fit mentioned in the text (continuous line) and with a fit of the form A^α (broken line), ref. [9].

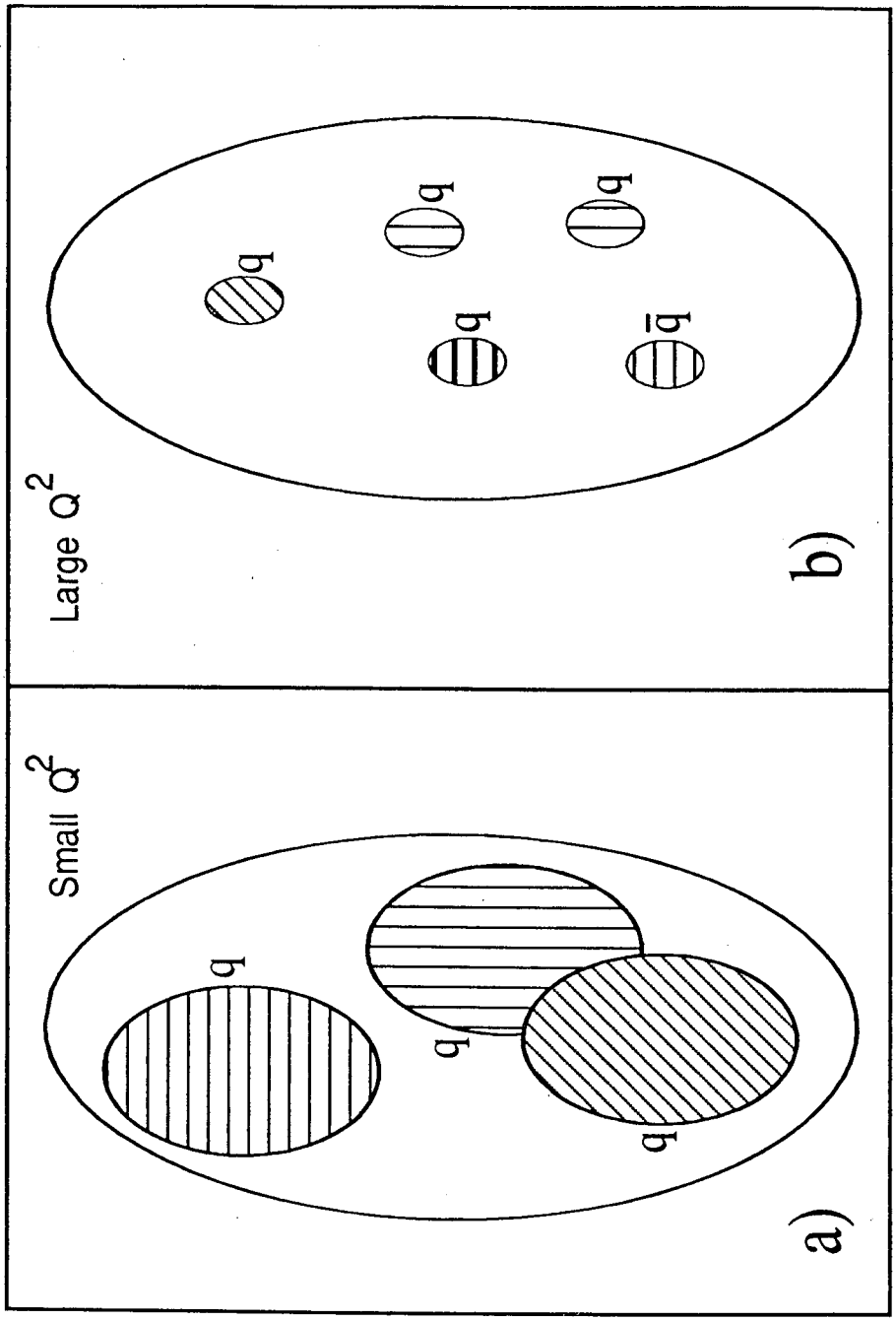

Figure 1

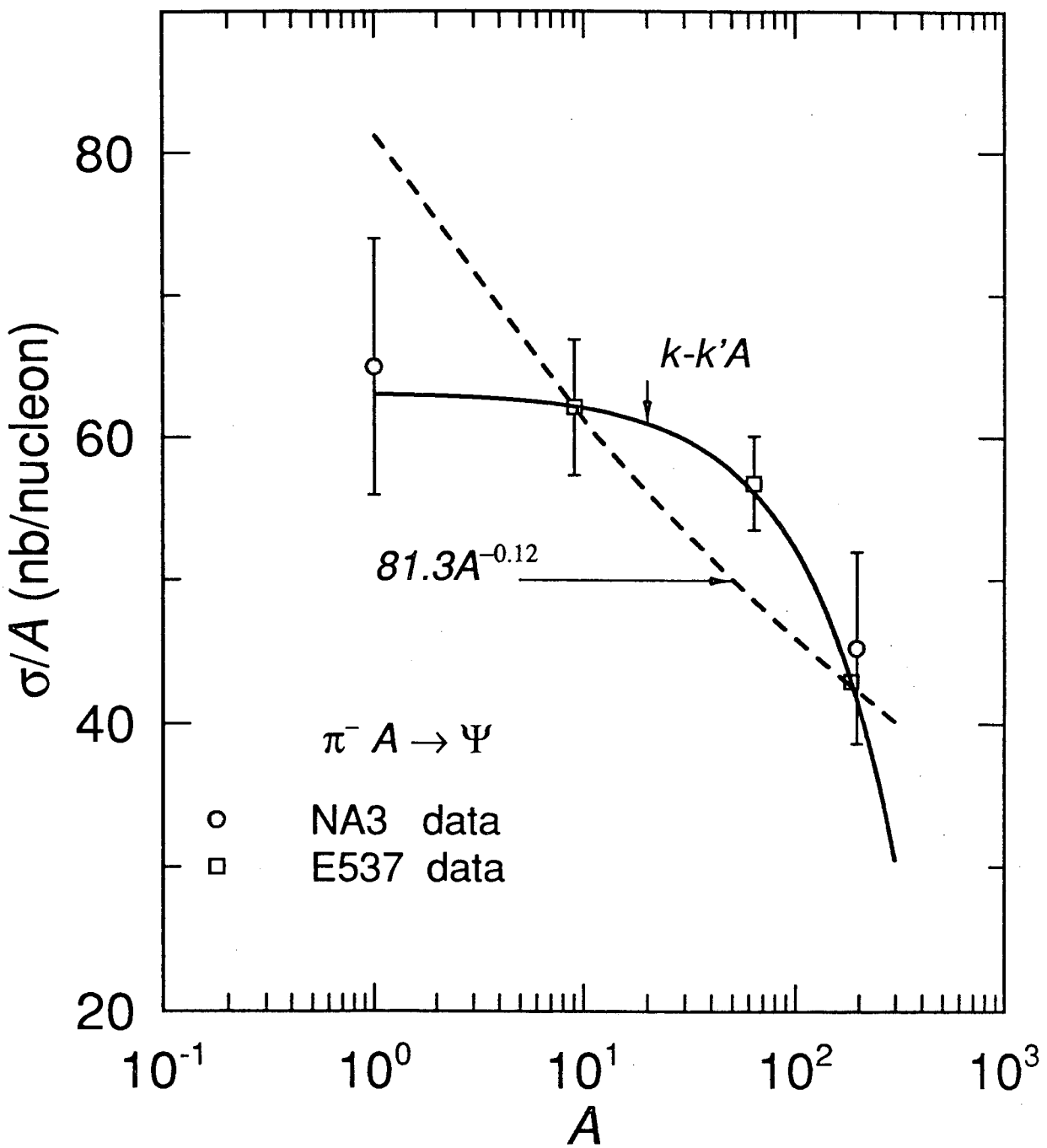

Figure 2

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